Poured Earth as concrete

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Abstract:
In order to pour an earthen material in a liquid state, as a concrete, technologies used by concrete and ceramic industries can be transferred to the field of earthen construction. Two different methods should be employed simultaneously. The first relates to theories of grain packing that have led to models of Apollonian packing and spaced packing, commonly used for the development of cement concrete (ultra high performance concrete and self-leveling concrete). It concerns the optimization of the granular skeleton of natural materials. The second relates to the dispersion of the colloidal fraction of earthen materials. In natural soils, clays are organized as porous aggregates composed of several tens of particles. These aggregates trap water that is not used to liquefy the mixture. The dispersion of these aggregates, releasing this interstitial water, liquefies the earthen material without adding water. This dispersion is obtained by adding a small proportion (on the order of a few tenths of a percent by mass relative to the dry material) of deflocculating agents such as those commonly used for the development of industrial ceramics. The combined action of these two methods leads to a solid material that does not crack while drying, and can easily be implemented at a viscosity comparable to that of vibrated concrete with the same tools than those employed by the concrete industry (cement mixer, shuttering, vibrating needle). This new technique is particularly suited for the implementation of slabs and other horizontal surfaces, and also for vertical walls.

1 INTRODUCTION

Earthen construction provides a number of advantages: local raw materials, low energy manufacturing, interesting hygrothermal behaviour. However, for a more extensive use, it can sometimes be necessary to optimize the manufacturing process or to improve the mechanical behaviour of this material as well as its durability.

For 2000 years, earthen construction techniques have hardly changed. However, at the scientific level, the various constituents of earth (aggregates, clay and water) have provided some of the most innovative subjects of scientific investigation of the last twenty years. Compared with dry and wet granular media (Bocquet et al., 1998), earth brought an additional level of physicochemical complexity at the finest scale of clays (Van Damme, 2001). The emergence of nanoscience and the physical chemistry of colloids and interfaces will undoubtedly contribute to the understanding of phenomena occurring in these materials: what is the nature of the forces responsible for the cohesion of particles? What is the role of surface interactions between the clay particles in the viscoelastic and rheological behaviour of the saturated material? What is the role of capillary water in the cohesion of earth?

These scientific questions arise for other materials such as, for example, cementitious materials (Pellenq and Van Damme, 2004). Indeed clays present many similarities with the calcium silicate hydrate, the main cement hydrate (Viallis-Terrisse, 2000). From the technological and industrial points of view, outstanding advances also prepare a favorable ground for a more innovative use of earth materials. For instance, the enhanced properties of self-compacting and self-leveling concretes are partly due to the use of cement dispersing agents and a better distribution of the granular packing (Vernet, 2004, Flatt et al., 2004). Similarly, in the field of industrial ceramics, effective dispersants and binders are used for shaping before firing.

The improvement of the properties of earthen materials can benefit from expanded research and findings applicable to industrialised materials. Following this idea, we applied the two main advances cited before (optimisation of granular packing and use of dispersing agents) to earthen materials.

The purpose of this paper is to present the first experimental results obtained through this research program. The effect of dispersing agents on the rheological behaviour of soil suspensions is presented. Then mortars are prepared and characterised by uniaxial compression tests. The results show that the use of dispersing agents leads to higher fluidity and compressive strength.

2 MATERIALS AND EXPERIMENTS

2.1 Soil

Natural soil from a quarry in Dauphiné (France) has been used in this study. This soil is suitable for rammed earth construction. It was sieved at 100µm. The particle size distribution is presented in Figure 1. A mineral analysis by X-ray diffraction mentions the presence of the following elements: quartz, clays (illite and muscovite) and alkali compounds (albite and microcline). The specific density has been measured with a helium pycnometer: 2.61 g/cm^3. The soil is stocked at ambient temperature and ambient hygrometry in the laboratory.

Standardized siliceous sand, with a specific density of 2.65 g/cm^3, is used to prepare mortars and compressive samples. Its particle size distribution is presented in Figure 1.

2.2 Additives

Two polymer additives have been selected in this paper for their dispersing effect: (1) Na-HMP: sodium hexametaphosphate $Na_6O_{18}P_6$, and (2) PAA: sodium salt of polyacrylic acid $(C3H4O2)_n$ with a molecular weight of 2100 g/mol. Both of them are widely used in the ceramic industry for their dispersing and deflocculating properties.

The dispersing mechanisms that can be expected by using such additives are the following: adsorption of the molecules at the surface of clay particles, electrostatic repulsion between the particles with adsorbed molecules, steric repulsion between the chains of macromolecules adsorbed on clays (Lewis, 2000, Fontaine and Anger, 2009). These electrostatic and steric forces keep the particles well dispersed.

Dispersant adsorption is highly dependent on the electrostatic interactions between the dispersant and the clay particle surface. Thus the surface chemistry of the solid phase and the solution properties of the polyelectrolyte are important parameters, and these parameters depend on the pH and the ionic strength of the solution. These considerations oblige to work properly in well-defined laboratory conditions, using pure water with controlled quality, in order to observe reproducible results.

2.3 Rheological characterization of dilute suspensions

Some of the authors of this paper have shown interest in the rheological approach to understand the physico-chemical mechanisms involved in the implementation of earth in a plastic state (Anger et al., 2009). The same approach is used here to characterize the effect of dispersants on the rheological behaviour of earth.

As it is expected that these polymers will interact only with the finest particles, we chose to work on suspensions containing only the soil fraction smaller than 100µm. It is also expected that the action of the polymers will be exacerbated in a dilute suspension rather than in a concentrated paste (mud). Thus, we decided to study the relationship between the rheological behaviour and the polymer content on dilute suspensions containing a 36% vol. of solid particles in water.

We start by preparing a large batch of dilute suspension of earth. Some reverse osmosis water is stirred in a beaker with a magnetic shaker. The earth is sifted and slowly poured into the vortex of water. When all the earth has been added, the beaker is covered with a plastic film to limit evaporation. The suspension is stirred for 24 hours.

After 24 hours, several 80 mL samples are prepared with different concentrations of dispersant: 0%, 0.05%, 0.2%, 0.5%, 0.8%. These mixtures are stirred again for 5 minutes for homogenization, and then characterized by rheology.

Rheological characterization is carried out with a co-axial viscosimeter Haake VT500. The liquid suspension is introduced between the two coaxial cylinders of the viscosimeter. The external cylinder is fixed and the internal cylinder can rotate either at a constant rotation speed (Ω) or at constant shear stress (τ). The shear rate γ' (or gradient of speed inside the fluid) is directly proportional to Ω.

The shear rate is increased from 0 to 1000 s^{-1} within 2.5 min, maintained constant during 30 s, then decreased to 0 s^{-1} in 2.5 min. We obtain a rheogram, in other words a diagram showing the shear stress versus the shear rate of the suspension analyzed. The studied supensions behave like Bingham plastic liquids, and their rheogram can be described by the Bingham relation which is a two-parameter model :

$$\tau = \tau_S + \eta_{plast} . \gamma'$$

where τ_S is the yield stress below which the fluid cannot be sheared, and η_{plast} is the plastic viscosity : the lower it is, the easier is to shear the liquid, once the threshold is exceeded. The weaker these parameters are, the more fluid the suspension is.

The rheological behaviour is determined on the basis of the descending rheogram. Such a procedure allows the samples to be characterized in the same agitated state. Two measures are performed for each sample to verify that the measure is reproducible and that the suspension is not altered during the experiment.

2.4 Optimisation of particle size distribution

Earthen materials used for construction are commonly described according to their granulometry: an earth may be qualified as sandy, fine, rocky, silty, clayey, etc. Each earth is a mix of grains with different sizes and the proportions change from one earth to another.

The packing of solid particles is of essential importance to the understanding of granular materials used in different size classes and related problems which appear in many fields of science and industrial processes, such as in civil engineering or ceramics.

A proper packing of grains is really important, first of all to improve the placement of the material, reduce shrinkage, facilitate the drying process and secondly to improve its final properties like its compressive strength or abrasion resistance. The optimization of particle size distribution (PSD) is the way to achieve a good packing.

In cement concrete, ingredients with a wide range of PSDs are combined. Therefore, different approaches can be found for the composition of concrete mixtures. Many authors have worked on this topic since the 1900s and have offered various solutions. The mix design concept discussed here and applied to earth consists in the proportioning of different grain sizes to formulate a continuously graded material. This idea is realized by the formulation of a mix using the equation of cumulative volume fraction from Andreasen:

$$CPFT = (D/D_{max})^q \qquad (1)$$

with CPFT being the “Cumulative Percent Finer Than”, D being the particle size, D_{max} being the maximum particle size and q being the distribution moduli.

Particle size distributions for the fine fraction of Dauphiné soil, the siliceous sand and the mortar mix for mechanical characterization are summarized in the Figure 1.

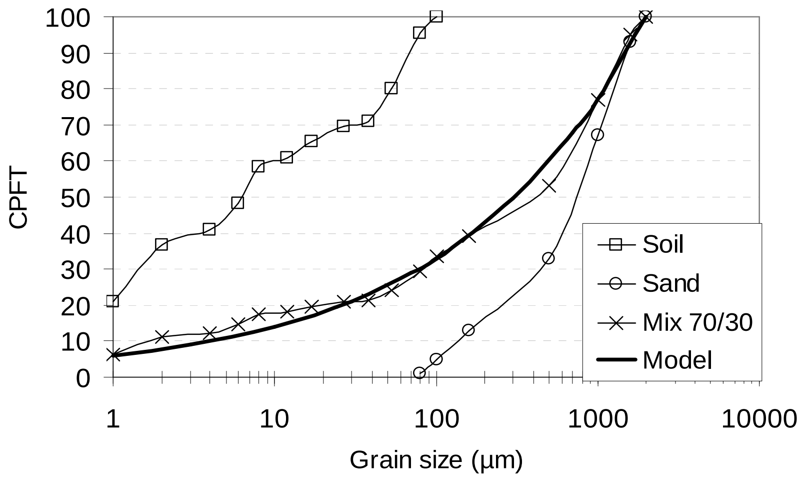

Figure 1 Particle size distributions

The mortar mix elaborated to produce samples for compressive tests is based on soil fines and standardized siliceous sand. In order to obtain a very good particle packing, the proportions of each constituent are defined in accordance with Andreasen’s model. This model, one of the most commonly used in the field of ceramics, indicates a distribution moduli between 1/3 and 1/2 to reach the best packing (Dinger, 2000). Our mix shows a good fitting with the distribution corresponding to q=0.37, noted “Model” in Figure 1. This mix corresponds to 70% in weight siliceous sand plus 30% soil fines. In this particular case, proportions in weight are equivalent to proportions in volume due to the close specific densities of raw materials.

2.5 Uniaxial compressive tests

Conventional mechanical tests concerning building materials remain simple and usually measure only one characteristic. The uniaxial compressive test is very common, but the majority of compressive strength values given in the scientific literature are inaccurate because the sample is not loaded in purely uniaxial compression (Fontaine, 2004, Morel, 2007, Mollion, 2009). If the compressive test is perfectly carried out, with no restraint from the machine plates and with direct strain measurement during the test, the intrinsic behaviour of the material can be assessed accurately.

To achieve this, we must overcome the edge effects induced by the friction between the sample and the compression plates. It is also necessary that the surfaces of the sample be parallel and smooth. Therefore, in this study, great care has been taken in the preparation of samples and the execution of compression tests.

Three different mortars are prepared with the soil/sand mix, with the optimised particle size distribution presented before: (1) reference mortar without dispersing agent, (2) with PAA, (3) with Na-HMP. The polymer content introduced in mortars (2) and (3) is equal to 0.5% in weight compared to the mass of fine soil. This quantity has been chosen on the basis of the rheological results presented below.

The fine particles are first mixed with freshly filtered reverse osmosis water and the dispersant. The preparation is mixed for 1 hour in a mortar mixer, then packed in a sealed bag. It is then kept for 24 h at 20℃. Then this mixture is again introduced into the mixer and the standard sand is incorporated. The mortar is mixed for 5 min at low speed and 5 min at high speed. The amount of water is adjusted to obtain a similar consistency for the three mortars. This consistency corresponds to a spread of 15.5 cm after 15 shocks on a standard shock table.

Cylindrical samples (diameter 30mm, height 55mm) are prepared by casting the preparation with shocks to help the material to spread. The samples are demoulded after 24 hours and left to dry at room temperature in the laboratory.

A fine earthen mortar is applied after one week on the surfaces of the cylinders to obtain very smooth and parallel surfaces. The samples are placed in a climatic chamber (20℃ and 50% relative humidity) until cons tant mass is reached, typically within a few days.

The uniaxial compression tests are performed on an INSTRON 8562 electromechanical machine. A roller is placed above the specimen to make up for parallelism defects. Oiled plastic wrap is placed between the specimen and each compression steel plate, in order to reduce friction. A LVDT sensor +/-10mm measures the displacement between the compression plates. An extensometer (gauge length 25mm) is placed directly in contact with the specimen and measures the deformation in the central portion of the sample, where the stress field is homogeneous.

3 RESULTS

3.1 Rheology

Viscosity measurement results for Dauphiné soil suspensions are presented below on Fig.2 and Fig.3. The effects of Na-HMP and PAA on the viscosity of the suspensions are very similar. The optimum polymer content is 0.5% for both additives. The plastic visosity is divided by 3 with both dispersing agents, which represents an important reduction of viscosity. The yield stress is drastically reduced with small amounts of additives, about 0.5% in weight. This drastic reduction of yield stress indicates that the suspensions which exhibit a shear thinning behaviour without a dispersing agent, operate a huge change and exhibit, at the optimum of the dispersing agent, a behaviour close to a newtonian fluid. These important reductions of both rheological parameters at the same water content result in a real difference in the fluidity of the suspensions.

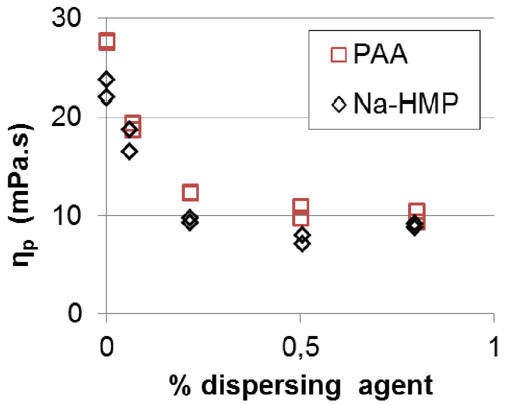

Figure 2 Plastic viscosity of suspensions with 36% vol. fraction of soil.

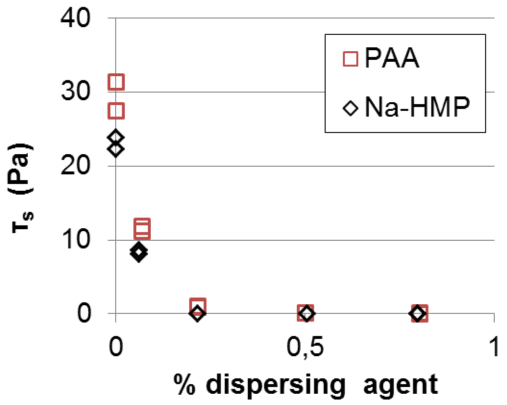

Figure 3 Threshold shear stress value of suspensions with 36% vol. fraction of solid particles.

This remarkable similitude between the effects of both additives on the earthen suspension studied here suggests that the mechanisms of dispersion involved are very similar. This was not expected at such a high level due to the complex nature and numerous different constituants in the fine fraction of Dauphiné soil.

These rheological results are of great interest for the future. They show the potential of possibilities to transfer the physico-chemical knowledge from other fields involved with the very fine particles.

3.2 Mechanics

The three mortars presented above were characterized in uniaxial compression. Fig 4. shows that the curves obtained for the four samples from the same series are very reproducible. This helps to validate the quality of the tests done.

The results from the compression tests performed on the three materials are given in Tab.1, and the Fig.5 shows the effect of the two dispersants used on the water content w_{init}, the dry mass ρ_{dry}, and the compressive strength f_c. In this figure, the values are normalized to facilitate comparisons. We see that the addition of PAA or of Na-HMP allows reducing the amount of water necessary for the implementation of earth mortars, at a defined consistency. It also shows that the dry density is slightly increased by the addition of the dispersant. The most striking result is the strong increase in terms of compressive strength: it is multiplied by 1.8 for the mortar containing PAA, and by 1.6 for the mortar containing Na-HMP, as compared to the reference mortar.

Such an increase in resistance cannot be due only to the very small increase in density. It is very likely that the use of dispersants leads to a different microstructure, with a more homogeneous distribution of pores and a better organization of clay platelets, for example. Microstructural characterizations are being made to better understand the origin of this phenomenon.

These first results seem very promising. They open an interesting path for the implementation of unstabilized earth concretes, without the need for a hydraulic binder.

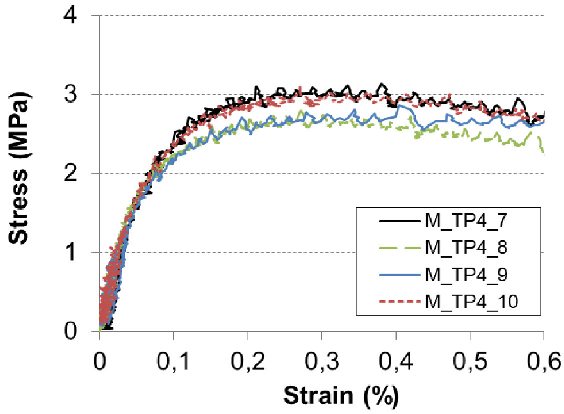

Figure 4 Uniaxial compressive behaviour of earthen mortars without dispersant.

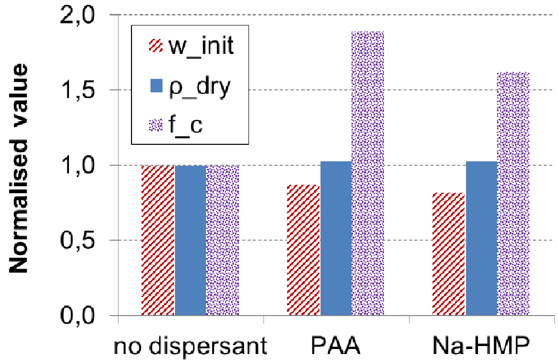

Figure 5 Effect of dispersing agents on macroscopic properties.

	dispersing agent	number of samples	w_{init} (%)	ρ_{dry} (g/cm^3)		f_c (MPa)	
				mean	std	mean	std
M_TP4	no	4	15.1	2.002	0.006	2.97	0.17
M_TP5	0.5% PAA	5	13.2	2.061	0.017	5.62	0.23
M_TP6	0.5% Na-HMP	5	12.4	2.062	0.015	4.81	0.16

Tab. 1 Results of the mechanical characterizations of earthen mortars

4 CONCLUSION

The goal of the study presented herein is to transfer some of innovations from the fields related to cementitious materials and industrial ceramics and apply them to earthen construction. First, the authors optimized the granular packing of their soil so as to obtain a solid material with low porosity. Then, they characterized the influence of dispersants on the soil's rheological and mechanical properties.

Experimental results show on one hand that the use of very small amounts of polymer dispersants can greatly reduce the viscosity and yield stress of dilute suspensions of soil. In the case of an earth mortar with a granular optimization, this results in a lower amount of water needed for its implementation, to obtain the desired consistency. Thus, the addition of a dispersant could help reduce the drying time for an earth concrete. On the other hand, the mechanical characterization of earth mortars shows that the addition of a dispersant can greatly increase the compressive strength of earth. This result is particularly interesting because it opens new ways to explore and achieve unstabilized earth concretes, with a resistance that could match the mechanical properties of earth concrete stabilized with a hydraulic binder, without affecting the hydro-regulating properties of natural earth.

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